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# Aspheric Optical Systems

P. A. MERIGOLD

*Non-spherical lens surfaces are a tool of modern optical design.*
*Though known for over three centuries,*
*they only became economical to manufacture a few years ago.*
*Now they are appearing in high-speed and high-performance camera lenses.*

It is to Descartes that history attributes the first suggestion that the use of non-spherical lens surfaces may reduce optical aberrations. In the publication *La Dioptrique* of 1638 he discloses the geometrical construction for a single lens free from spherical abberation. The construction described had one surface a portion of an ellipse, whilst the other surface was spherical having its centre of curvature at one of the foci of the ellipse.

The ellipse together with the parabola and the hyperbola are simple examples of what may be described as aspheric or non-spherical surfaces of revolution, each having particular properties when used as refracting or reflecting surfaces. They constitute, with the circle, a set of curves described as conic-sections, since all of them may be produced by cutting across a cone or cylinder.

More generally, our aspheric surface can be considered to be a deformation of a spherical surface of equal vertex radius. The effect of the deformation on a refracting or reflecting surface is to advance or retard an incident wave front relative to the action of the spherical surface by itself. A general surface of revolution, symmetrical about an optical axis (this axis being chosen as the x direction) can be represented by the equation $x = ay^2 + by^4 + cy^6 + \ldots$, for the purpose of calculation.

Whilst the conic-sections are more easily determined and perhaps easier to manufacture and test, they represent a limitation in the design of aberration-free optical systems.

For example, whilst the ellipse may be shown to produce a point on axis free from spherical aberration, either the incident or emergent beam must be parallel to the lens axis.

Thus no correction is made for the oblique field aberration of, say coma and astigmatism.

It is therefore often preferable to utilise more complex surfaces other than conic-sections in designing a system utilising aspheric surfaces. This may aid correction of residuals from elsewhere in the system and the off-axial aberrations. A good example of this point is the Schmidt system (page 89). Whilst it is over three hundred



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years since Descartes described his aplanatic lens using an elliptical surface, and whilst there appear to be obvious advantages in designing certain systems with aspheric surfaces, there are comparatively few lenses available commercially of photographic quality that utilise aspheric components.

The reasons behind this involve design, manufacture and economics, to quote but a few. Perhaps however the single major drawback to progress in this aspect of optics has been the difficulty in evolving methods for producing aspherics consistently, and to an equivalent quality of spherical surfaces, at similar or competitive cost.

## EARLY ASPHERICS

Prior to this century very little was done by way of either design or manufacture of surfaces other than conic-sections. In the mid-17th century there was a period of activity in which the limitations of the refracting telescopes led to the inception of the reflecting telescopes of Gregory, Cassegrain and Newton. In the same period Sir Christopher Wren suggested an engine for the production of hyperbolic surfaces. At this time little was understood as regards abberation of optical systems; however, Gregory suggested that conic-sections could improve a system otherwise employing spherical mirrors. Newton had turned to reflecting systems in his belief that refracting systems could not be corrected for chromatic abberation. The simplicity of his system having a parabolic reflector, a plane mirror and an eyepiece, is such that today most amateur telescope makers adopt it. (The parabolic mirror has similar properties to the ellipse in that a beam parallel to the axis is reflected to a single focus free from spherical aberration.)

More recently the development of photographic lenses stimulated a greater desire to produce aspheric surfaces. Little is disclosed as to attempts prior to the appearance of the Cooke Triplet by Dennis Taylor at the turn of this century, but between 1908 and 1922 Carl Zeiss took out several patents with respect to both the design and manufacture of lenses using aspheric surfaces. One of these[1] describes a triplet characterised by the feature that the last surface of the objective is deformed. Earlier attempts by Zeiss to manufacture aspherics were concerned with the moulding of components.

Many attempts since this time have been concerned with moulding aspheric curves, but little success has resulted for surfaces of photographic lens quality. This process however has an important application in the manufacture of components for condensing systems, where the quality of imagery is quite crude compared to the photographic image. Nearly every modern projector has some form of aspheric correcting surface in the condensing system. Many materials other than glass have been moulded successfully, these include benzyl-cellulose, pheno-plastics, polystyrene, polymethyl-methacrylate, and epoxy resins.[2,3]

## THE SCHMIDT SYSTEM

When Bernhardt Schmidt introduced the system, that now bears his name, in 1930, he sparked off a new line of thinking in photographic optics. It was simple, comprising only a thin aspheric corrector plate and a spherical mirror. His discovery lay in the positioning of the corrector plate

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ve to the mirror. He placed that plate aperture stop at the centre of curva- of the mirror. The corrector plate is parallel in form having one surface rical to correct not only the axial ical aberration but also the oblique e defects. Schmidt's first camera ed at $f$1·75 having an aperture of 14 s with a focal length of 24 inches, ing a 16° field.

e focal plane of the earlier Schmidt ns is intermediate between the plate he mirror and is necessarily curved ex towards the mirror. Subsequent fications have led to the focal plane brought exterior to the mirror idt-Cassegrain system) and attempts been made to flatten the focal plane acing a plano-convex lens at this In essence however the Schmidt n has provided a means of achieving relative apertures with reasonable ngles without the large mass of glass ubsequent absorption and flare of ing systems.

of interest to examine how Schmidt his first correcting plate. In a simple ous manner he cemented his plane- d glass plate to a drum. By evacuating in the drum he caused the plate to ew hundredths of an inch, and then d and polished the distorted plate to low spherical curve in the normal r. On readmitting the air and releas- e strain the plate took on the aspheric on one side.

e these early days, many methods been attempted in figuring Schmidt tors, these include electromagnetic applied in annular rings, and various g techniques.[4]

Apart from their astronomical uses, Schmidt systems have found many other applications, amongst them projection systems for television purposes, where the problem of a curved focal plane can readily be overcome by providing a suitable radius on the surface of the cathode ray tube face.

Whilst other mirror systems have been described involving the use of ashperics (Linfoot,[6] Baker,[7] Maksutov[8] and Wayman[9] amongst others) a logical development of the Schmidt reflecting system has been the Dioptric Schmidt[9]. This replaces the convergent mirror by a convergent objective, and retains the front aspheric corrector as a relatively low-power convergent element having a slight convex curve on the one side, and an aspherical surface on the other. The original construction of the Dioptric Schmidt, consisted of two doublet components and an aspheric correcting lens, and was a 5 inch $f$1·4 covering a full field of 36°. Subsequent derivatives by Warmisham[10] and Wreathall[11] have yielded apertures of $f$1·0 and $f$0·7. Lenses of this nature retain the further feature of the Schmidt system having a curved focal plane, but in this instance concave to the convergent member. This fact was of small consequence for their main application—cine radiographic work—where the film was simply curved to suit.

The Dioptric Schmidt has the advantage over the classical Schmidt in that for photographic purposes where focal lengths are shorter than in astronomical uses, the focal plane is exterior to the optical system, thus the film holding mechanism does not obscure the incident light, enabling full use to be made of the extremely wide apertures.

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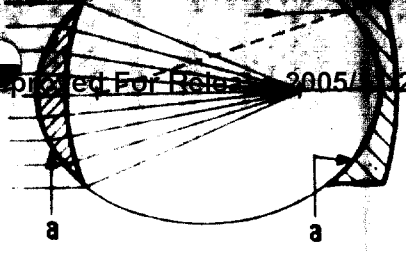
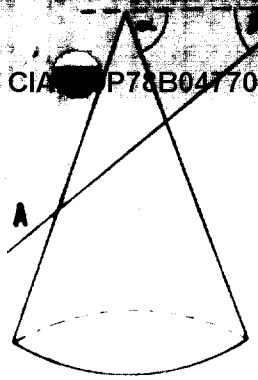
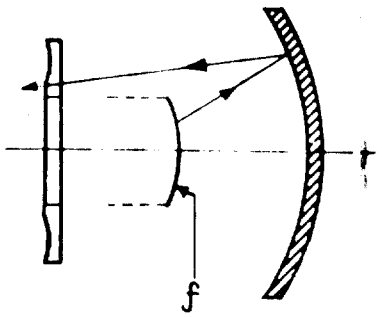
*e simplest aplanatic lenses with non-ical surfaces* (left) *have one surface each ical* (a).

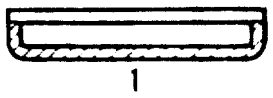
*mple non-spherical surfaces are conic ns—i.e. a cut* (AB) *across a cone. If gle β = O, the conic section is a circle. β is smaller than α, the conic section ellipse; when β = α, the section is a ola; and when β is larger than α, the n is a hyperbola.*



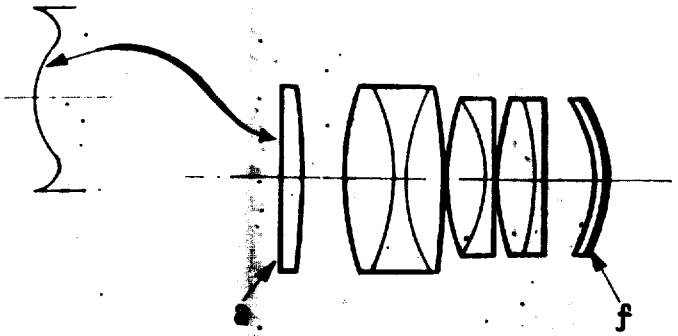




*e classical Schmidt system uses a ical mirror to project the image on a d focal p (f). It also has an aspheric tor plate (the surface here is exaggerated). hmidt produced his corrector plates by g a flat glass plate across the top of a m vessel (1). On evacuating the air ent the plate (2). On grinding down the e to a shallow spherical curve as shown e dotted line, the plate after releasing acuum produced the required aspheric e (3).*



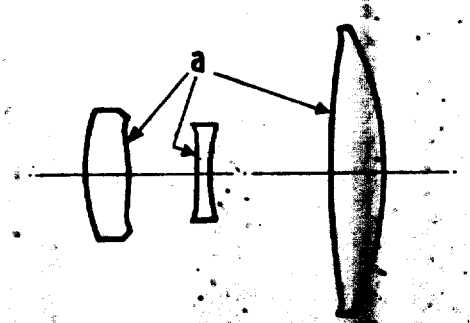



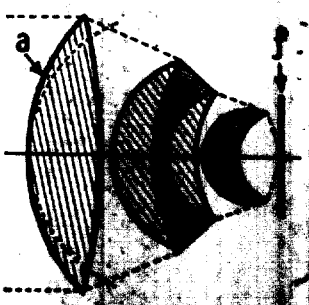
*e Dioptric Schmidt f0.7 lens has a component with an aspheric surface* (a) *own exaggerated—and produces its e in a c focal plane* (f).




***the 6 inch f5.6 triple aspheric triplet each element has one spherical curve he other an aspheric* (a).**

***oshido's five-element triplet* (right) *ves an aperture of f0.519 with com-ively few elements, one having an eric surface* (a). *The dotted line indicates pherical curve. The focal plane* (f) *t touches the strongly curved rear lens.***



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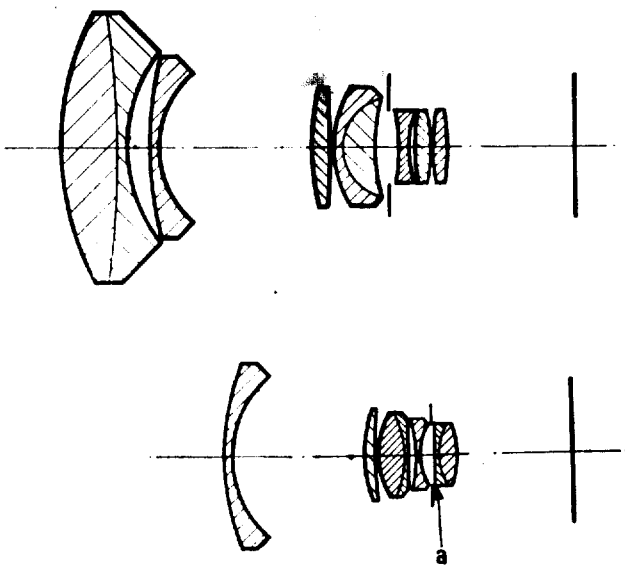
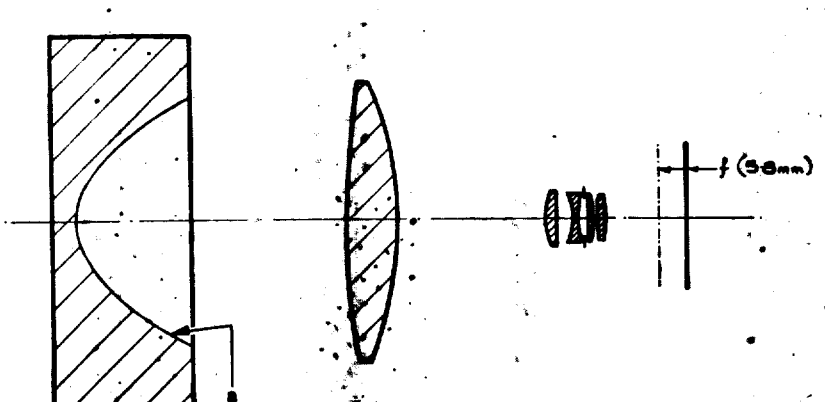
*he 12 mm. Elgeet Golden Navitar f1.2 an aspheric surface* (a) *as a corrector plate g the place of the last component. With ical components only, extra elements d be required.*

*he Rank Taylor Hobson 25 mm. Cooke d Panchro Series III for 35 mm. natography further illustrates the saving ble with aspheric elements. The original n* (upper diagram) *had all spherical ces and 9 elements to yield an aperture 1.8. An inverted telephoto construction ed to provide the necessary back focus se on a reflex camera type; that makes lens rather long and bulky, leading to uction of the view of other lenses on camera lens turret.*

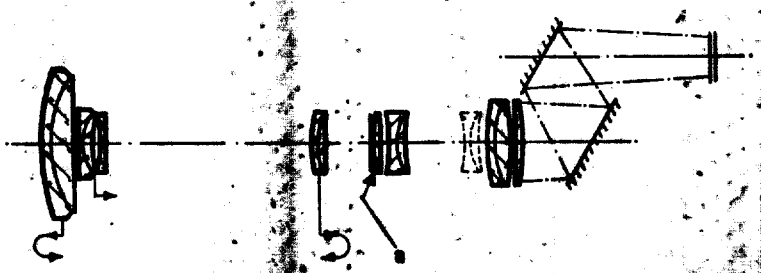
*The later design* (lower diagram—same e) *uses only 7 elements and has one eric surface* (a). *The aperture is f2, but using fewer elements the effective trans- ion (T2.2) remains the same. The lens the same time shorter and less bulky.*




*the inverted telephoto system of the mm. Kinoptic for 16 mm. cameras the t component has a parabolic surface* (a). *demonstrates the intelligent use of an eric surface to control the higher order ts of astigmatism and distortion, which usually the biggest problem in an inverted photo lens covering such a large angle of 3°.*




*Aspheric elements also help in zoom lens ign. This is the Rank Taylor Hobson o 40 inch Varotal III f4 for television eras. There is one aspheric surface at* (a) *the lens has two zoom ranges: the nal range from 4 to 20 inches at f4, and urther range of 8 to 40 inches at f8, ined by moving the negative member in the rear to the dotted position.*



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## THE MANUFACTURE OF ASPHERIC SURFACES

The commercial manufacture of ordinary spherical lens components involves three basic processes: (a) the grinding of the initial curve on the glass blank (usually performed with a cup-shaped diamond wheel); (b) the smoothing of this curve with a cast iron lap and abrasive powder until a fine "grey" is produced; and (c) finally the polishing of the grey surface with rouge or cerium oxide and a pitch lap.

During the polishing process the lens or block of lenses is figured until the correct radius and uniformity of curvature is obtained. The figure is inspected by examining the contour by means of interference fringes produced between the lens and a test plate, using monochromatic light.

Naturally an aspheric profile cannot be maintained on a lens surface by rubbing lens with a rigid aspheric lap or polisher. Some considerable departures from the above procedures are necessary.

Individual aspheric lenses and Schmidt corrector plates may be produced by efficient hand lapping, using flexible laps with graduated facets, and then polishing with flexible laps consisting generally of pitch, or pitch and felt facing on sorbo rubber. This is an uneconomical process commercially and involves careful optical testing and repeated re-figuring of the aspheric surface. To produce aspherics in commercial quantities and in a manufacturing time which compares favourably with the time involved in producing a normal spherical lens, costly machinery of extreme accuracy is required.

In place of the cup-shaped diamond wheel used for grinding spherical lenses, a thin disc-shaped diamond wheel with a sharp periphery or a cylindrical wheel with a sharp corner, is used for grinding the aspheric profile. Alternatively a single point diamond may be used. The lens is mounted on a spindle of extreme accuracy. Whilst this rotates at a fast speed, the edge of the cutting tool traverses across the lens surface in such a manner that the required aspheric profile is produced to within an accuracy of 0·00001 inch. In order to work to this degree of accuracy, extremely careful design is required of all slideways and pivots on the generating machines and also the room in which the machine is used must be temperature controlled.

Present-day machines for producing aspheric lenses on a commercial scale are computer-controlled. Data from the computer is fed into the aspheric generator in the form of either rectangular or polar co-ordinates. As many as 400 sets of co-ordinates, each to 6 places of decimals may be used for a lens no more than 1 inch in diameter. This information is, by means of electronic controls, transmitted to the tool carriage of the machine to cause the cutting tool to traverse the lens surface and produce the correct profile.

### DIRECT POLISHING

With spherical lens surfaces a smoothing stage follows the cutting or grinding, before the lens is finally polished. With aspheric surfaces the smoothing stage introduces further difficulties of profile control, and is therefore omitted.

However, the surface produced by the aspheric generator must then be sufficiently fine in texture to allow the lens to be

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polished directly without smoothing. The polishing process is extremely difficult, for it must remove approximately 0·0005 inch of glass to transform the grey into a polished surface. This has to be done in such a way that the aspheric lens profile does not change from its original grey shape by more than 0·00002 inch. So the total thickness of glass to be removed from the surface of the lens (by means of a flexible polisher) is 25 times as much as the tolerance allowed on profile accuracy.

To achieve this the lens is accurately mounted in a cell before polishing. The polishing stroke of the machine and lens rotation during polishing is also precision-controlled.

## PROFILE CHECKS

There are several methods available for checking the errors in profile of a finished aspheric lens.

Where the lens is a large one (as in the case of a Schmidt correcting plate), zonal masks may be used to allow a pinhole or graticule image to be formed by only one zone of the plate at a time. Measurement of the focus of each of these zones permits graphic estimation of the errors in the plate profile.

Local polishing can then correct the surface.

In the case of smaller units the aspheric component may be mounted in a cell as part of the complete lens assembly with which it is to be used, and a collimated star image examined through a microscope. The assembled lens may also be tested by projecting a test graticule on to a screen.

A more refined method is to mount an inductance or capacitance type probe on to the tool carriage of the aspheric generator. The lens is mounted in a cell on the machine spindle. The probe traverses the surfaces in such a manner that a recorder graphs the errors in the lens profile. By suitably amplifying the output from the probe, magnifications of up to 50,000 may be used. So a ½ inch displacement on the record graph represents an error in the lens profile of 0·00001 inch.

Various other process lenses have been employed.[11]

## MODERN ASPHERIC SYSTEMS

During the last few years aspheric elements have appeared more frequently in commercially available lenses. Technological advances in mechanics and in electronics have made the production of any aspheric surface to a consistent quality comparable with spherical surfaces a feasible proposition.

In the last five years several companies have announced photographic lenses with aspheric surfaces. These include Perkin-Elmer and Elgeet in the United States, Les Appareils de Precision Kinoptik of France, and Rank Taylor Hobson in England. (Heinz Kilfitt in Germany has marketed also bispheric lenses. In these a surface has two different spherical curvatures, one for the centre of the component and another at the edge.)

Aspheric surfaces can correct an optical system in a variety of ways.

The most radical application is to replace all components by aspheric ones, and a triplet lens on these lines has been proposed by Perkin-Elmer. It is difficult to assess the significance of the resulting improvement over triplets of similar field coverage

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and aperture, but such a lens would be appreciably more expensive to produce commercially.

Owing to the complexity of aspheric curves, the elements have to be worked as single components rather than a quantity in a block, as is normal in manufacturing all but very deep spherical curves. Generation and polishing of the non-spherical surfaces also takes longer, though—as manufacturing techniques improve—the cost of producing the surface itself may become comparable to that for a spherical one.

In most present-day aspheric lenses a single aspheric element is therefore employed to improve residual corrections or to reduce the number of components needed for a given performance. The use of an aspheric element may also yield a shorter lens construction—an important consideration when the lens has to be mounted on a turret with other lenses (e.g. in cine and television work) and could obscure the viewpoint of other lenses on the same turret.

Examples are the 12 mm. Elgeet Golden Navitar $f$ 1·2 for 16 mm. cameras, and the Rank Taylor Hobson 25 mm. Speed Panchro Series III $f$ 2·0[13] for 35 mm. cine work. The latter, with seven elements and one aspheric surface, replaced an earlier considerably bulkier nine-element system of all-spherical components.

The aspheric surface in this case provided complete correction of spherical aberration and contributed to higher order coma correction. This left the other surfaces free to be utilised fully for the correction of astigmatism, distortion and chromatic aberrations.

The saving of lens components by aspheric surfaces in elaborate lens systems can make the use of aspherics economical in manufacture.

Although the surface itself may be more expensive to produce than a spherical one, the reduction in the number of spherical components to be polished, edged and surface-coated can offset this. For example in the Taylor-Hobson 25 mm. $f$ 2·0 Series III Speed Panchro, there is a reduction of four surfaces from the previously designed system. Also, the reduction in the number of elements increases light transmission; in the case of the Taylor, Taylor & Hobson lenses mentioned above the aspheric system with as geometric aperture of $f$ 2·0 yielded the same transmission (T 2·2) as the all-spherical $f$ 1·8 system.

Current developments in aspheric surfaces have further coincided with progress in zoom lenses. The Taylor-Hobson Varotal III Zoom lens for television outside broadcasts is the first to incorporate such a surface. As zoom camera lenses require a minimum of two moving members together with fixed members to maintain focus throughout the zooming range, the resulting systems are inevitably very complex.

Aspheric elements undoubtedly reduce the numbers of elements needed. However, because of the complex nature of the change in aberration contributions, of both fixed and moving members in front of the stop, throughout the zoom range, it is difficult to forecast what additional benefits may eventually be derived, in simplification and improvement of specification, from using aspheric surfaces.

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## EXTENDING PERFORMANCE LIMITS

Eventually, the main role of aspheric systems will be the extension of lens speed and performance beyond the limits possible with all-spherical components. The aspherised complex triplet of Shoroto Yoshido, a Japanese lens designer of the Sendai Science Laboratory, achieves a relative aperture of $f$ 0·519 from 5 elements, and indicates the possible trend to wider aperture objectives.[14] Whilst there may be a need for lenses of such wide aperture at present, this trend could be forestalled by introduction of faster image receptors.

It is more likely however that the most immediate application of aspheric surfaces will be in the reduction in the number of components in established constructions, where the boundaries of aperture and field angle appear to have been stretched to the limit. In addition, this reduction in the number of lens elements will also improve image contrast.

Many large optical companies now use electronic computers which enable the designer to investigate more fully the possibilities of the various constructions. The computer is a powerful tool and greatly reduces the sheer labour of relatively simple mathematics which hampered the design of lenses with aspheric surfaces in the past. The computer can also be used to tabulate the large amount of co-ordinate data required to accurately define a non-spherical surface of revolution.

The problems of design, however, are perhaps small compared with those still to be solved, in the production of the aspheric surface at a cost comparable with the spherical surface. If this can be achieved, then the day of the man in the street having an aspherised triplet, in his £20 camera, will soon follow.

Acknowledgment. *I am grateful to Mr. G. O. Rawstron (Rank Taylor Hobson) for his advice in preparing this article, and for his contribution of the section on the manufacture of aspherics.*


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2 *British Patent* Nos. 561, 503; 586, 844; 626, 530; 649, 015.

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11 *British Patent* No. 689, 110.

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13 P. Merigold and Rank Taylor Hobson; *British Patent* No. 880, 848.

14 *Perspective*: **2**, No. 2, p. 182 (1960).